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Short and Long Term Performance of Concrete Structures Repaired/Strengthened with FRP

by

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Certificate of authorship/originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Muhammad Ikramul Kabir

Date:

To my parents because of whom I have found my existence in the vivid and vibrant Earth

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List of publications based on this thesis

Conference publications

1. **Kabir, M. I.**, Shrestha, R. & Samali, B. 2013, 'Experimental study on durability of CFRP-concrete bond subjected to temperature, humidity and outdoor environment' *Proceedings of the Fourth Asia-Pacific Conference on FRP in Structures (APFIS 2013)*, 11-13 December 2013, Melbourne, Australia
2. **Kabir, M. I.**, Shrestha, R. & Samali, B. 2012, 'Effects of temperature, relative humidity and outdoor environment on FRP-concrete bond' *Proceedings of the 22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM 22)*, 11-14 December 2012, University of Technology, Sydney, Australia.

Journal publications

3. **Kabir, M. I.**, Shrestha, R. & Samali, B. 2013, 'Experimental and analytical investigation on the repair of damaged concrete beams with CFRP' (submitted to *Australian Journal of Civil Engineering*)

Abstract

Fibre Reinforced Polymer (FRP) composites have lately become a popular choice for strengthening and/or repairing of reinforced concrete (RC) structures due to their advantageous properties such as high strength- to-weight ratio, high corrosion resistance and easy application process. As the performance of FRP bonded RC structures depends on the effective stress transfer between FRP and concrete, extensive research has been conducted on the FRP-concrete bond system under short term loads. However, studies on the long term performance of FRP-concrete bond subjected to environmental conditions are very limited.

Experimental studies on the long term performance of FRP strengthened structures to-date include the study of the effect of various environmental conditions using a variety of test set-ups such as pull-off, bending tests of beams and direct shear tests. However, the available studies based on various conditions and set-ups make it difficult to compare the findings. As the effectiveness of FRP-strengthening schemes, either used for flexural or shear strengthening, lies in the shear stress transfer between FRP and concrete, study of FRP-concrete bond subjected to different environmental conditions by direct shear tests were suggested by some of the researchers. Even sensitivity of this set-up to environmental conditions was also reported. Therefore, more research with similar test set-ups to create a large database of FRP-concrete bond behaviour under various environmental conditions can be of immense value. In addition, using very high temperature for accelerated ageing was found to be very common in available literatures. However, in reality structures may not be exposed to such high temperatures and using high temperature may lead to conservative prediction of long-term properties. Moreover, unavailability of test data for FRP-concrete bond subjected to natural ageing observed in the existing literatures necessitates the investigation on FRP-concrete behaviour under natural environment.

In regards to the short term performance of reinforced concrete beams strengthened and/or repaired with FRP, extensive research have been conducted to-date in terms of experimental and analytical study. Some of these studies have also proposed design guidelines. However, the equations for prediction of load carrying capacity of severely damaged repaired beams, especially, considering the strain hardening after yielding are not recommended.

Considering the identified gaps in the previous research on long term performance of FRP-concrete bond system and the short term performance of RC beams strengthened and/or repaired with FRP, the research study presented in this dissertation has mainly focused on the experimental investigation of the long-term performance of carbon FRP and glass FRP-concrete bond under three separate environmental conditions, namely, temperature cycles, wet-dry cycles and outdoor environment up to 18 months. The secondary objective is to investigate the effectiveness of typical FRP-strengthening schemes, used for strengthening of reinforced concrete beams, in the repair of severely damaged beams.

The long term performance of two types of FRP (CFRP and GFRP)-concrete bond is studied by extensive experimental investigations using single shear tests (is referred to as pull-out tests). The maximum temperature of the temperature cycles is intentionally kept below the glass transition temperature of epoxy resin to avoid any over-degradation. In the wet-dry cycles, temperature close to ambient is maintained. Also, outdoor environmental exposure is applied to address the unavailability of test data of natural ageing of FRP-concrete bond system. Pull-out tests conducted after exposure durations are analysed based on the pull-out strength, failure modes and strain distributions along the bond length. In addition, material properties, namely, CFRP tensile strength and modulus of elasticity, and concrete compressive strength are determined to understand the effect of changing material properties on the pull-out strength by correlation of bond strength with failure modes. Curve fitting of shear stresses against slips of only CFRP-concrete bond is conducted to determine the fracture energy release rate and the effect of environmental conditions on it. In addition, interface laws are proposed for control and exposed conditions based on an existing model. Results obtained for long term performance of bond systems provide interesting findings due to imposed environmental conditions. Based on the observations, strength reduction factors for CFRP and GFRP-concrete bond are proposed.

The short term performance of FRP-repaired beams is investigated both experimentally and analytically. Three severely damaged beams, fabricated from conventional concrete (normal concrete with water, cement and aggregate) and non-conventional concrete

(concrete with additives such as fibres and rubbers) are repaired with CFRP for flexure. Anchorage provided by complete CFRP wrapping at two ends and mid-span is found to be effective for preventing the debonding of FRP at least partially. Analytical study is conducted to understand the effect of existing steel reinforcement on the response of repaired beams under flexure. Considering the strain hardening of steel after yielding, equations are also proposed for better prediction of load carrying capacity of the repaired beams and compared with experimental results.

Finally, all the major findings of the two areas of research are summarised and recommendations for future research are made.

List of abbreviations and acronyms

ACI	American Concrete Institute
AFRP	Aramid Fibre Reinforced Polymer
AS	Australian Standard
ASTM	American Society for Testing and Materials
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
CFS	Carbon Fibre Sheet
CoV	Coefficient of Variation
CSS	Carbon Strand Sheet
CZM	Cohesive Zone Model
DIC	Digital Image Correlation
DMTA	Dynamic Mechanical Thermal Analysis
EG	E-Glass
ERR	Energy Release Rate
FA	Fly Ash
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
GRC	Glass Fibre Reinforced Cement
IRRH	Interface Region Relative Humidity
IRT	Infrared Thermography
LED	Light Emitting Diode
LEFM	Linear Elastic Fracture Mechanics
LVDT	Linear Variable Differential Transformer
MOE	Modulus of Elasticity
NLFM	Nonlinear Fracture Mechanics
PC	Portland cement
PP	Polypropylene
QIRT	Quantitative Infrared Thermography
RC	Reinforced Concrete
RH	Relative Humidity
RTC	Residual Thickness of Concrete

SBR	Styrene Butadiene Rubber
SCCB	Single Contoured Cantilever Beam
SG	Strain Gauge
TSF	Time Shift Factor
UV	Ultraviolet
VCCT	Virtual Crack Closure Technique

List of notations

A	A constant in the test condition for accelerated ageing with Arrhenius principle
A_f	Cross sectional area of FRP
a_f	Depth of equivalent rectangular stress block of FRP strengthened/repaired beam
$A_{f_{anchor}}$	Area of FRP anchor
A_s	Area of steel reinforcement
$A_{s_{bottom}}$	Area of bottom steel reinforcement
$A_{s_{top}}$	Area of top steel reinforcement
b	Width of beam
b_c	Width of a concrete member
b_f	Width of FRP plate or sheet
c	The depth of neutral axis of a beam / interface cohesion in a Mohr-Coulomb envelope
c_f	A regression constant for fracture energy
C_{th}	Threshold interface moisture content beyond which no further degradation occurs
d	Depth of bottom steel axis from the top of the beam
d'	Depth of top steel axis from the top of the beam
E_a	Activation energy
E_c	Elastic modulus of concrete
E_f	Tensile modulus of elasticity of FRP
Es	Tensile modulus of elasticity of steel
f_c'	Concrete compressive strength
f_{ctm}	Concrete surface tensile strength
f_f	Axial stress in FRP plate or sheet
f_{fu}	Ultimate tensile stress in FRP at rupture

$f_{s\mathrm{Res}}$	Residual strength of steel
f_t	Tensile strength of concrete
f_u	Ultimate tensile stress of steel
f_y	Yield stress of steel
G_f	Fracture energy/fracture energy release rate
G_{Ic}	Fracture energy under mode I loading
G_{IIc}	Fracture energy under mode II loading
h	Height of beam
J	Energy release rate at a debonding tip
k	Reaction rate constant with respect to a temperature T
k_f	Geometrical factor related to FRP width and concrete width
L_e	Effective bond length
M_n	Nominal moment capacity of beam
P_f	Applied load in FRP
$P_{\max}$	Ultimate bond strength / ultimate load at bond failure
R	Universal gas constant
$s_{\max}$	Slip value at the maximum shear stress
T	Absolute temperature in Kelvin
t	Time
t_f	Thickness of FRP sheet or plate
T_g	Glass transition temperature (sometimes referred to as heat distortion temperature) of polymer
w_f	Width of FRP anchor
Y	Tensile strength retention value
β_L	Length factor of FRP-concrete bond
β_p	Width factor of FRP-concrete bond
δ or s	Slip between FRP and concrete
δ_f	Maximum slip of FRP-concrete bond

ε_f	Axial strain in FRP
ε_{f0}	Initial strain of concrete at the level of FRP reinforcement
$\varepsilon_{fe_{anchor}}$	Effective strain of FRP anchor
ε_{fu}	Ultimate tensile strain of FRP
ε_{s0}	Initial strain the steel reinforcement
ε_u	Ultimate tensile strain of steel
ε_y	Yield strain of steel
$\sigma(t)$ or $P(t)$	Composite strength after an exposure time *t*
σ_0 or P_0	Composite strength for unexposed condition
σ_∞	Composite strength after infinite exposure time
σ_{db}	Maximum axial stress of FRP at debonding failure
τ	Interface shear stress / a characteristic time dependent on temperature
$\tau_{\max}$	Maximum shear stress at failure of bond
ϕ	Friction angle in a Mohr-Coulomb envelope

Table of contents

List of tables

List of figures